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Rapidity and p_t dependence of identified-particle elliptic flow at RHIC

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Abstract. Elliptic flow has been measured by the BRAHMS experiment as a function of transverse momentum and pseudorapidity for the Au+Au reaction at $\sqrt{s_{NN}} = 200\ GeV$. Identified-particle $v_2(\eta, p_t)$ values were obtained with the two BRAHMS spectrometers at pseudorapidities $\eta \approx 0$, 1, and 3.4. The results show that the differential $v_2(\eta, p_t)$ values for a given particle type are essentially constant over the covered pseudorapidity range. It is suggested that the dominant cause of the observed fall-off of the integral v_2 values going away from mid-rapidity is a corresponding softening of the particle spectra .

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The large azimuthal anisotropy in particle production observed near mid-rapidity at RHIC has been taken as evidence for the formation of an almost ideal fluid corresponding to a strongly interacting quark-gluon plasma[1]. Pressure gradients of the thermalized medium formed early in the relativistic heavy-ion collisions result in azimuthally asymmetric particle production, with the highest final particle densities occurring in the reaction plane. Elliptic flow is identified with the v_2, 2^{nd}-harmonic term of a Fourier expansion of the azimuthal angular dependence of the particle production. Near mid-rapidity, the identified particle $v_2(p_t)$ values are found to be near the hydrodynamic limit, with a particle mass dependence below 2 GeV close to that expected from hydrodynamic models[2, 3]. The v_2 values integrated over transverse momentum are found to fall off going away from mid-rapidity, dropping by about 35% by pseudorapidity $\eta = 3$, with similar behavior seen in Au+Au reactions from $\sqrt{s_{NN}} = 19.6$ GeV to 200 GeV[4].

As part of its program to determine how the physics at RHIC changes in going to forward rapidities[5], BRAHMS has measured v_2 as a function of transverse momentum for pions, kaons, and protons at angles (pseudorapidities) $90^{\circ}(\eta = 0)$, $40^{\circ}(\eta = 1)$, and $4^{\circ}(\eta = 3.4)$. The experiment has previously presented evidence that the charged-particle and pion $v_2(p_t)$ behavior at forward rapidities differs little from that seen near mid-rapidity, a somewhat surprising finding in light of the integral v_2 results[6]. The

‡ For the full authorlist and acknowledgements see the appendix of this volume.

new analysis explores this behavior further by studying additional particle channels and by analyzing the $v_2(p_t)$ behavior together with the associated particle spectra.

The orientation of the reaction plane with respect to the laboratory system was determined using azimuthally symmetric rings of Si strip detectors and scintillator tile detectors in the BRAHMS Multiplicity Array, and plastic Cherenkov radiators mounted to phototubes in one of the experiment's Beam-Beam counter arrays[7]. The general procedure for determining the reaction plane and the corresponding reaction-plane resolution is described by Poskanzer and Voloshin[8]. The reaction plane corresponding to the second moment of the angular distribution is found with

$$\Psi_2 = \frac{1}{2}\sum_i \frac{w_i \sin(2\phi_i)}{w_i \cos(2\phi_i)}, \tag{1}$$

where the sum is over all detector elements with geometric weighting factors w_i and azimuthal angle ϕ_i.

The angular correlation with respect to the reaction plane of particles detected in the BRAHMS mid-rapidity and forward spectrometers determine the observed v_2 values, with

$$v_2^{obs} = \langle \cos(2[\phi - \Psi_2]) \rangle . \tag{2}$$

Here the angular bracket denotes an average over all events of a given class, such as all pions within a given range of transverse momenta. Since the BRAHMS spectrometers are small acceptance devices, all particle detected in the mid-rapidity spectrometer have $\phi \approx 0^o$, while those detected by the forward spectrometer have $\phi \approx 180^o$.

The true v_2 value, which is based on the actual reaction plane, is found from the v_2^{obs} value using the reaction-plane correction factor R, with

$$v_2 = v_2^{obs}/R. \tag{3}$$

The reaction plane correction for any given ring (or ring combination) is determined using two additional rings that are far enough apart so as to avoid autocorrelations. Considering rings A, B, and C, the reaction-plane correction factor for ring A is found as:

$$\mathrm{R_A}=\sqrt{\frac{\langle \cos(2[\Psi_2^A - \Psi_2^B])\rangle \langle \cos(2[\Psi_2^A - \Psi_2^C])\rangle}{\langle \cos(2[\Psi_2^B - \Psi_2^C])\rangle}} \tag{4}$$

The reaction plane resolution factor was typically in the range $0.18 < R < 0.25$.

Figure 1 shows the resulting values (closed symbols) of $v_2(p_t)$ for pions, kaons, and protons at the indicated pseudorapidities, selecting events in the 10% - 50% centrality class. The behavior for the three different particle species shows very little change with pseudorapidity.

The average value of transverse momentum for pions in the 10% - 50% centrality class at 90° is (475 ± 60) MeV/c, falling to (380 ± 45) MeV/c at 4°. These values are obtained by fitting a power-law dependence to the respective particle spectra. The softening of the particle spectrum going to more forward rapidities can have a significant effect on the integral v_2 values. This is illustrated in Figure 2. The insert shows an

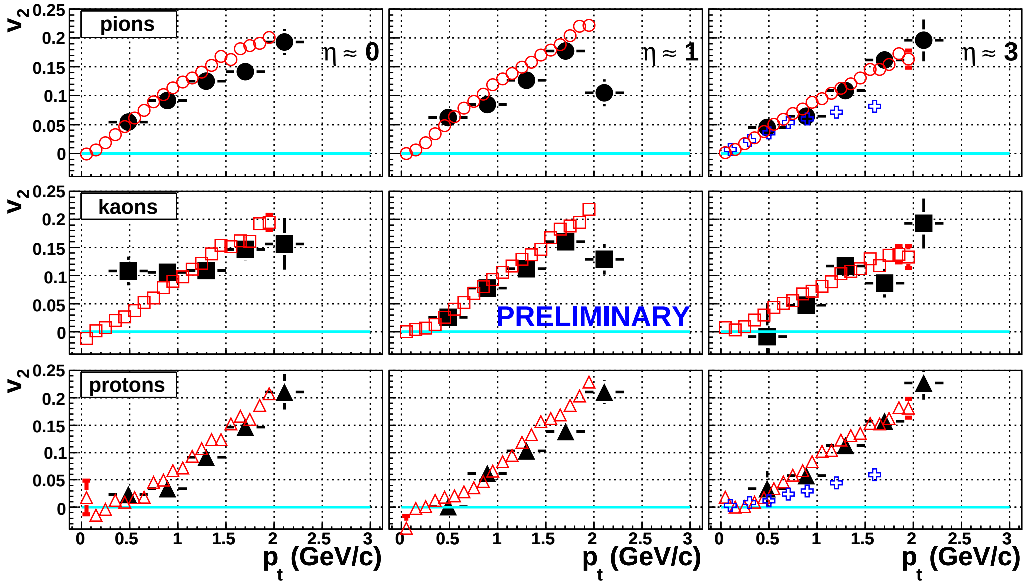

Figure 1. $v_2(p_t, \eta)$ for pions, kaons, and protons (filled symbols). Theoretical values based on the hydrodynamic calculations of Hirano *et al.* [9] are shown by the open circles, squares, and triangles. The open crosses correspond to $\eta \approx 4$ calculations using the AMPT model [10].

assumed form of $v_2(p_t)$ that is taken as being constant as a function of pseudorapidity. Folding this behavior with the experimentally observed normalized particle spectra for pions at 90° and 4° result in the solid and dashed lines of the main figure panel, respectively. The softer spectrum at the more forward pseudorapidity results in the weighted v_2 distribution peaking at a lower mean p_t value, resulting in a 22% smaller integral v_2 value than a mid-rapidity. Two-thirds of the observed integral v_2 change is then attributable to the softening of the particle spectrum.

The small change in the differential v_2 signal going from mid- to forward rapidity suggests a longitudinally extended region for the medium produced in the collision. Rapidity dependent changes in the radial flow or other rescattering behavior of the hadronic stage might then account for most of the fall off of the integral v_2 signal going to forward rapidities.

Hydrodynamic calculations are able to reproduce the observed behavior. This is seen by the open circles in Figure 1 which show the results of the hybrid hydrodynamic calculations of Hirano *et al.* ([9], and private communication) that include dissipative effects of the late hadronic expansion stage. Good agreement is found with the experimental results. The open crosses in Figure 1 show the results of the AMPT model for pseudorapidity $\eta = 4$. At this angle the string melting mechanism that allows for a good reproduction of mid-rapidity results has been turned off ([10], and private communication). Although the comparison is subject to poor matching of pseudorapidity, there is a suggestion that the longitudinal extent of the produced medium may be greater than that assumed in current AMPT calculations.

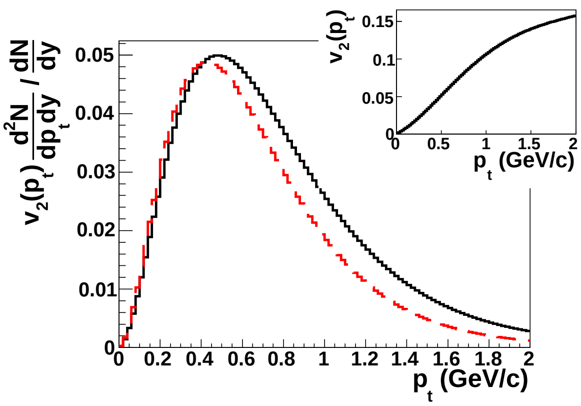

Figure 2. Illustration of how the softening of the particle spectra going to forward angles affects the integral v_2 values. The insert shows the general behavior of the differential $v_2(p_t)$ values for pions, which for this illustration is assumed to be independent of pseudorapidity. Folding this distribution with the corresponding experimentally observed pion spectra at 4^o and 90^o results in the dashed and solid curves, with integral v_2 values of 0.046 and 0.036, respectively.

In conclusion, BRAHMS has measured $v_2(p_t, \eta)$ for pions, kaons, and protons at $\sqrt{s_{NN}} = 200$ GeV for the Au+Au reaction. The results indicate a longitudinally extended region is produced where the eccentricity of the created medium and the corresponding pressure gradients remain remarkably constant. Hydrodynamic calculations with final stage dissipation are found to be in excellent agreement with the measured differential v_2 values.

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